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(54) **Coriolis-effect fluid mass flow and density sensor made by a micromachining method**

(57) An apparatus for measuring fluid mass flow and/or density has a generally U-shaped flow channel (107) formed in a cantilevered member (103) by a micromachining technique, such as by a lithography and etching process. A top cover (102) is bonded over the member (103) to enclose the channel (107), the bonding being made by an electrostatic or anodic bonding means. By vibrating the cantilevered member during fluid flow, and sensing the resultant motion, the mass flow and fluid density can be measured. Excitation and detection may be thermal, optical, electrostatic, piezoelectric or electromagnetic.

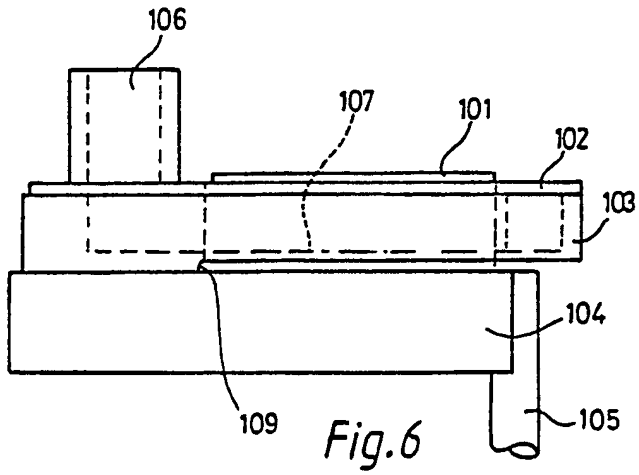

Fig.6

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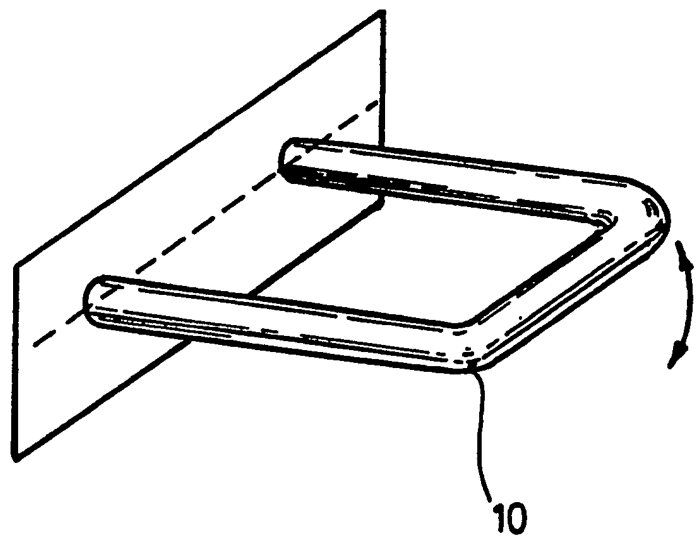

Fig. 1

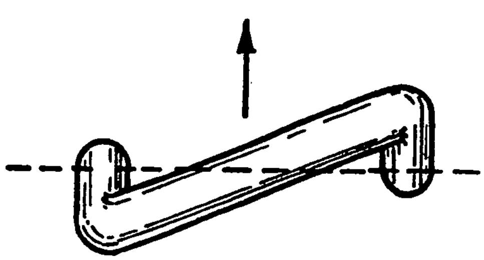

Fig. 2A

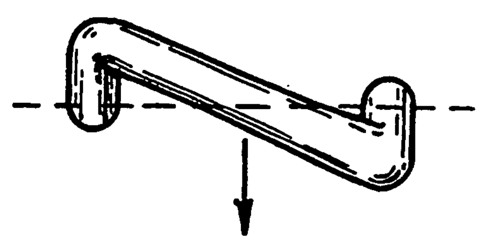

Fig. 2B

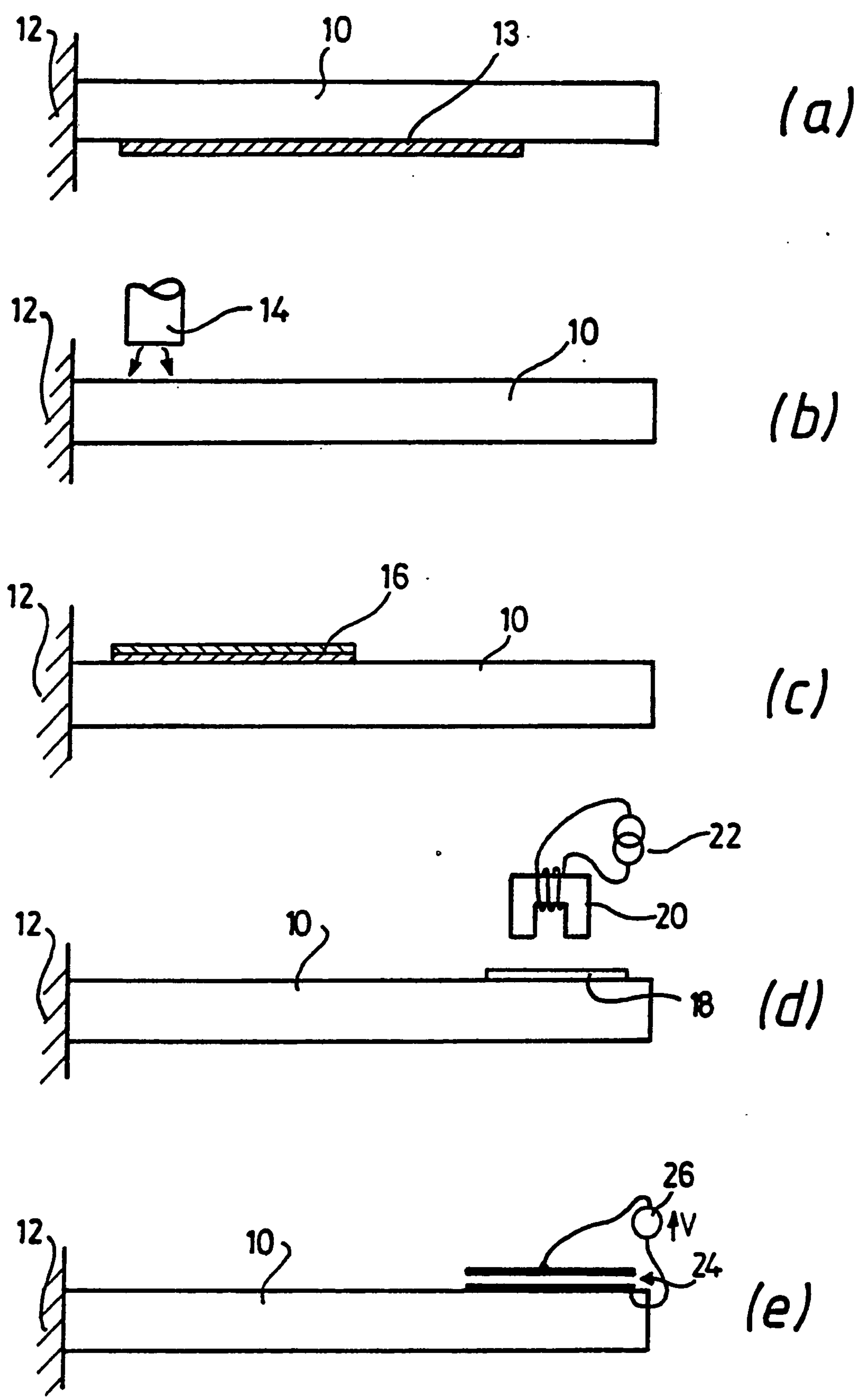

Fig.3

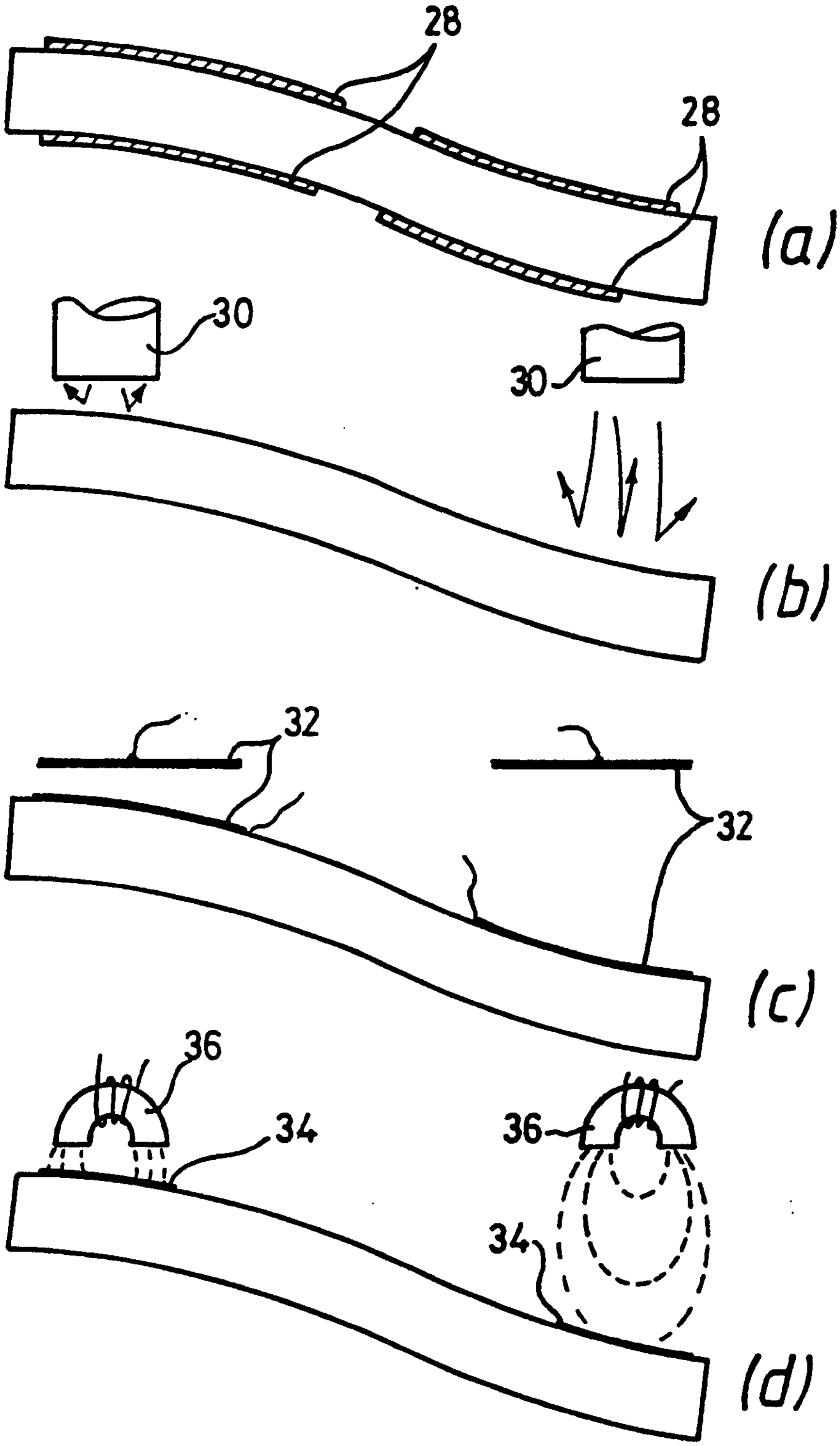

Fig.4

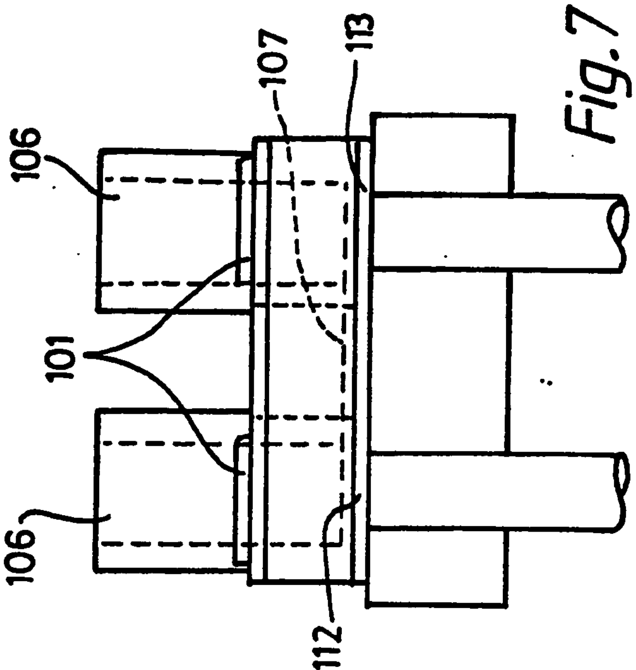

Fig.7

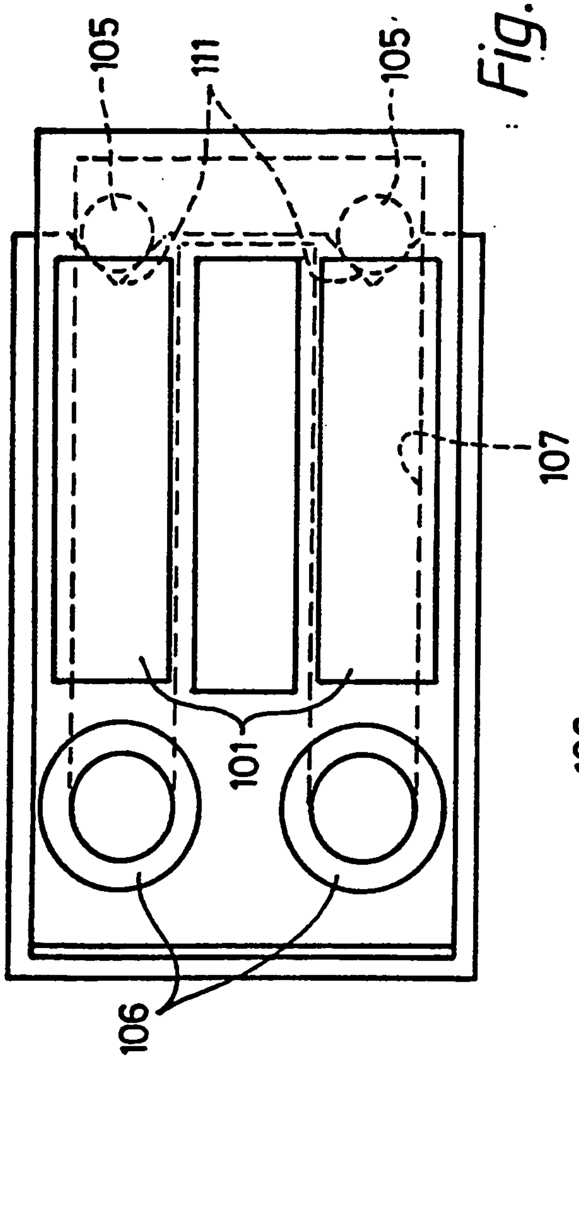

Fig. 5

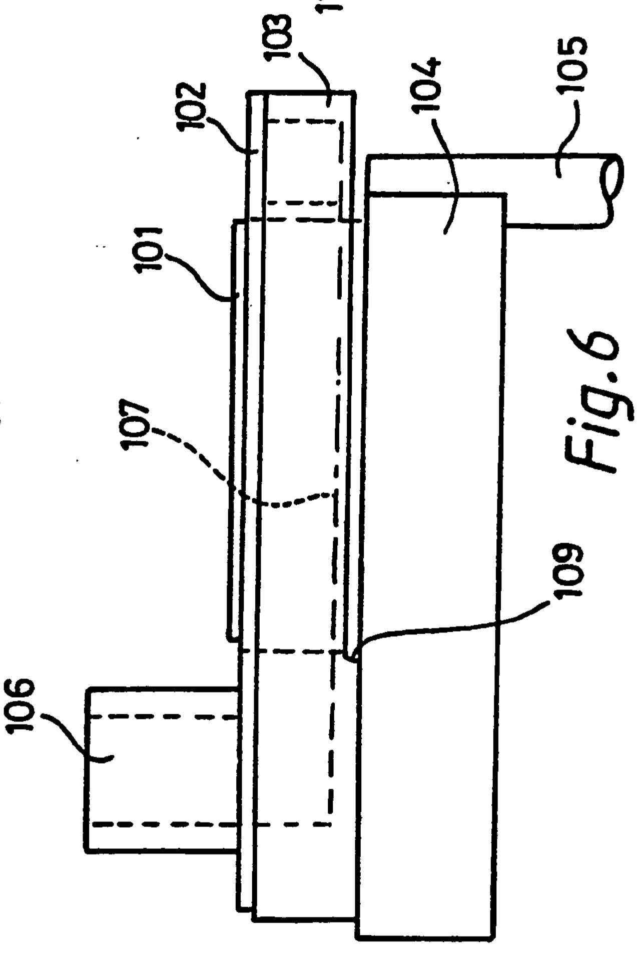

Fig.6

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Title: Fluid Mass Flow and Density Sensor

Field of the invention

The present invention relates to apparatus for measuring fluid mass flow and/or density, and to a method of constructing such an apparatus.

Background of the invention

Conventional Coriolis mass flow meters are relatively large devices, some tens of centimetres in length, often constructed from many components and sub-assemblies and typically measure true mass flow rates in the range 0.5 g/s to 150 Kg/s. The measurement of lower mass flow rates is achieved using other types of flow meter such as those based on differential pressure drops, turbines, metering pumps, thermal measurements and Doppler effects, however, these methods do not measure mass flow directly but are sensitive to fluid velocity or volumetric flow rate from which the mass flow may be derived, provided the composition of the fluid is known and its relevant properties well characterised.

Statement of invention

According to the present invention, there is provided an apparatus for measuring fluid mass flow and/or density comprising an enclosed flow channel generally of U-shape which is cantilevered at its ends, excitation means for

causing the free portion of the channel to vibrate, and detection means for monitoring the motion of the free portion, the flow channel being formed by a micromashing technique.

The micromachining technique may be of the type developed for the integrated circuit fabrication industry, and may for example comprise a lithography and etching process.

With these construction methods a mass flow and density sensor may be fabricated in a wide range of sizes with dimensions of the order of a few micrometers to a few centimeters. Therefore, the true mass flow measurement range of the Coriolis sensor may be extended to mass flow rates many orders of magnitude lower than those measureable by conventional devices.

In addition to this advantage, the present invention describes a configuration of sensor which only requires a relatively small number of simply formed micromachined components to comprise the complete Coriolis mass flow and density sensor unit. The process of micromachining is well established, involving lithography and etching processes, and does not form part of the invention described herein. The components formed by micromachining may be joined together by electrostatic (anodic) bonding, solder or cement to form the complete device.

The invention also extends to a method of so forming such a measuring apparatus.

Brief description of the drawings

The invention will now be described, by way of example

only, with reference to the accompanying drawings in which:

Figure 1 is a perspective view of the basic arrangement of a fluid mass flow and density meter;

Figures 2A and B are end views of the meter showing, in exaggerated form, its twisting in use;

Figure 3 shows side views (a) to (e) of alternative excitation techniques for the meter;

Figure 4 shows end views (a) to (d) of alternative detection techniques for monitoring the twist in the meter; and

Figures 5 to 7 are respectively views in plan, side elevation and end elevation of a preferred embodiment of the meter.

Detailed description

Conventional Coriolis mass flow meters are usually excited into resonant vibration by electromagnetic means, and the motions due to the Coriolis effect of the moving fluid mass are similarly sensed by electromagnetic means. The present invention described below employs thermal, optical, electrostatic, piezo-electric or electro-magnetic excitation and detection techniques.

Considering a U-tube geometry for the micromachined Coriolis mass flow and density meter shown in Figure 1, a U-tube cantilever 10 is excited into vertical oscillation or vibration by one of the techniques mentioned above.

When a mass flow of fluid passes through the U-tube 10 while it is vibrating as shown in Figure 1, the Coriolis forces due to the fluid motion cause the U-tube to twist in quadrature with the U-tube cantilever vibration, such that the instantaneous orientation of the U-tube end as it passes through the central point of oscillation is shown in Figure 2 - depending on the direction of fluid flow and velocity of vibration.

The magnitude of twist is proportional to the mass flow rate through the tube and may be sensed by measuring the relative phase shift in oscillation of each arm of the U-tube or by measuring the angle of the surfaces of the end of the tube or arms of the tube. The geometry of the Coriolis mass flow meter is not confined to a U-tube shape, a 'tennis racket' shape and straight tubes may also be employed.

Figure 3 illustrates a range of excitation techniques which may be employed to maintain oscillation of the U-tube or other shaped beam configuration in each case from a cantilever fixture point 12. These methods show respectively:

(a) a piezo-electric bimorph strip 13;

(b) photo-thermal excitation using anoptical fibre 14;

(c) a bimetallic strip or element 16 which is photo-thermally or electrically heated;

(d) electro-magnetic excitation using a magnetic force plate 18 attached to the end of the beam 10, and an

electromagnet 20 actuated by a current drive 22; and

(e) electrostatic excitation using capacitor plates 24 actuated by a voltage drive 26.

With the beam 10 in resonance, the torsional Coriolis forces applied to the structure as a result of the fluid flow through the U-tube may be ascertained by measuring either the torsional deformation of the structure apparent from the distortion of the U-tube end or from the phase difference between the oscillation of the U-tube arms.

Figure 4 illustrates a range of detection techniques which monitor the twisting distortion of the U-tube cantilever end. The methods shown utilise respectively:

(a) a piezo-electric technique with piezo-bimorph strips 28;

(b) an optical technique such as interferometery and variable reflective coupling back into optical fibres 30;

(c) a capacitive technique using capacitor plates 32; and

(d) an inductive proximity detection technique using inductors 34 and loading plates 36 mounted on the U-tube end.

The capacitive and inductive proximity sensing techniques may be used in an a.c. bridge circuit for sensitive detection of the cantilever twisting movement and good rejection of the fundamental cantilever oscillation movement.

From the excitation and detection schemes described it is possible to construct a device using different excitation and detection methods which can result in negligible breakthrough of the drive onto the output signal, enabling a low noise output signal to be obtained. The differential output from the two detectors provides the twist signal from which the mass flow rate may be determined, whereas the summed output may be used to determine the cantilever position and is used in a feedback circuit to maintain the cantilever resonance at its natural frequency and at a suitable amplitude. The natural frequency of oscillation is dependent on the fluid density within the cantilever U-tube and is used to determine that density. For a given device the mass flow is proportional to the ratio of the difference signal to the sum signal.

Referring now to the preferred embodiment of device shown in Figures 5 to 7, a U-tube cantilever is formed from two components: a channel section member 103, and a top cover 102. The channel section 103 comprises a plate of an etchable material which contains an open channel 107. The formation of this component is straightforward, using micromachining techniques known to one versed in the art thereof. The U-tube cover 102 is formed from a plate of a compatible material which may be similarly fabricated by micromachining and which is bonded to the top of the section 103 by any suitable process: for example electrostatic or anodic bonding is a well established technique for bonding silicon and metals to glasses. The top cover 102 contains two windows through which the fluid may flow into the channels 107 within the section 103. Two tubes 106 are anodically bonded or cemented to the top cover 102, to form the fluid inlet and outlet of the flow

and density sensor.

The cantilever U-tube and feed tubes assembly, comprising the parts 102, 103, and 106 is similarly bonded to a base plate 104 made of glass. This compatible material base supports a pair of optical fibres 105 which are used to analyse the position of each side of the cantilever end. The fibres 105 are set into V-shaped grooves 111 for alignment, and fixed with epoxy cement or other bonding technique. The fibre ends may be cleaved and polished after the bonding process. The curved sections 109, at the material interface, inhibit stress concentration at these points. Examples of suitable materials for these components are nickel alloy for the tubes 106, single crystal silicon for the channel section 103, and glass for the top cover 102 and for the base plate 104.

The cantilever assembly is maintained in its fundamental resonance by piezo-bimorph drivers 101 bonded to its surface on either the top or bottom or both. The feedback required for continuous mechanical oscillation is derived from the optical signals transmitted by the optical fibres 105 or from the electrical impedance of the bimorph drivers. Each of the fibres 105 in the present configuration form one arm of a two arm interferometer, such that the interferometer is sensitive to the difference in the gap lengths 112 and 113. This difference in the gap lengths, is determined by the twist of the U-tube cantilever introduced by the Coriolis forces imparted by the flowing fluid mass.

The density of the fluid in the U-tube cantilever assembly is determined from the natural frequency of oscillation of the beam which is reduced by the presence of the fluid

inside it.

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Claims

1. Apparatus for measuring fluid mass flow and/or density comprising an enclosed flow channel generally of U-shape which is cantilevered at its ends, excitation means tor causing the free portion of the channel to vibrate, and detection means for monitoring the motion of the free portion, thc flow channel being formed by a micromachining technique.

2. Apparatus according to claim 1 in which the flow channel is formed by a lithography and etching process.

3. Apparatus according to claim 1 or claim 2 in which the flow channel comprises a flat member into one face of which the channel is micromachined, and a cover secured onto said face to enclose the channel.

4. Apparatus according to claim 3 in which the member is made of a single crystal silicon and the cover is made of glass.

5. Apparatus according to claim 4 in which the member and the glass are bonded by electrostatic or anodic bonding.

6. Apparatus according to any preceding claim in which the excitation means comprises a piezo-electric bimorph strip.

7. Apparatus according to any preceding claim in which the detection means comprises an interferometer and a pair

of spaced optical fibres directed towards the free portion of the channel to detect twisting thereof.

8. A method of contructing an apparatus for measuring fluid flow and/or density having a cantilevered flow channel of generally U-shape, in which the flow channel is formed by a micromachining technique.

9. Apparatus for measuring flow mass flow and/or density substantially as herein described with reference to, and as shown in, the accompanying drawings.

10. A method of constructing an apparatus for measuring fluid flow and/or density substantially as herein described with reference to, and as shown in, the accompanying drawings.

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